Sensing and Navigation System for a Multiple-AUV Testbed

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LONG-TERM GOALS

The long-term goal is to enable the creation of a multiple-AUV testbed in which control strategies for network coordination can be studied in three-dimensional space.

OBJECTIVES

The objective of this project is to provide a sensing and navigation system that will support the coordination of multiple underwater vehicles in a freshwater, laboratory test tank. At Princeton University, an investigation into coordinating control strategies is already underway and an indoor multiple AUV experimental testbed is under development. The indoor, freshwater experiment allows for comprehensive testing of control architectures, low-level control laws and dynamics of a fleet of AUVs in an environment that can be controlled and manipulated as desired. A key challenge to operating a group of AUVs in an indoor tank or pool is the development of a sensing and navigation system that provides to each vehicle not only its own position and attitude but also the relative position and attitude of at least its nearest neighbors. The aim of the sensing and navigation system is to provide for this critical capability for a group of AUVs.

APPROACH

In order to create a testbed for experimenting with network control laws, it is necessary that each AUV not only navigates individually but also senses the relative position and attitude of its nearest neighbors. The sensing and navigation instrumentation is intended to address these needs using acoustic and optical solutions. To sense the absolute position of each vehicle we consider using acoustics at appropriate frequencies to minimize the reverberations from the walls. Three baseline stations are placed at the circumference inside the tank. Those three base stations will send out synchronized acoustic pings. Each AUV in the network will receive these acoustic signals as well as an RF-synchronization pulse. This allows for the on-board computation of each vehicle's global position, based on the known synchronization time and the known location of the base stations. The approach has the advantage to allow for additional vehicles in the tank without requiring additional acoustic energy in the tank that would lead to a deterioration of the position accuracy (scalability and multi-path reduction). Heading will be measured using a fiber optic gyro because of interference problems of the earth magnetic field with the steel tank. Relative position and attitude measurements will be determined two ways, and the two will be fused to get the best kind of information for feedback control. The first method will be to use radio-frequency (RF) communication via a central computer

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14. ABSTRACT

The long-term goal is to enable the creation of a multiple-AUV testbed in which control strategies for network coordination can be studied in three-dimensional space.

15. SUBJECT TERMS

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such that each vehicle can be provided with the absolute positions of its nearest neighbors. Each vehicle can then calculate the relative positions of its neighbors by subtracting its own position from its neighbors. The second method will use optics to determine directly the relative position and attitude of a vehicle's nearest neighbors. This includes the use of position sensitive devices (PSDs), commercially available blob trackers and stereo computer vision. The PSDs also have the potential to be used for basic communication directly between vehicles (e.g., by means of sensing and then decoding light pulses). Besides being used as a navigational tool, the blob-tracker (CMU-CAM) and the stereovision system will also be used for sensing objects in the environment, for example, in the context of a search task or an obstacle avoidance task. In the case of the blob-tracker we are limited to track simple geometries (Blobs) with the advantage of having a Commercial-Off-The-Shelf (COTS) product with a high update-rate for position information and an adaptable data interface. The on-board vehicle controller has to be designed for a reasonable bandwidth (~10 Hz) and ease of use for a large user community. The choice was made to implement the Matlab/Simulink environment for its user interface and widespread use in the controls community and Mathworks' new XPC target toolbox that allows for real-time computations on standard computer hardware such as a PC104 computer.

Ralf Bachmayer (Research Staff) and Naomi Leonard (PI) lead this effort. Robert Sorenson (Technical Staff) and Edward Fiorelli (Graduate student) and Derek Paley (Graduate Student) as well as a number of undergraduate students support this effort on a part-time basis.

WORK COMPLETED

As part of the larger testbed development, we have designed and completed most of the construction of four "Princeton Grouper" vehicles. The design of the second and third generation was slightly altered based on the experience of the former generations. This development has significantly improved the manageability of the platforms. Only minor changes to the propulsors were necessary. The controller, motor and propeller characteristics for the initial set of thrusters were successfully matched, and this allowed for a quick reproduction. We have developed a smart interface for our sensors and actuators using a common communication bus and a standardized protocol. In addition to the motor controller, the interface has been implemented on the depth sensor, temperature sensor, fiber optic gyro, inclinometer and on a battery monitor. The smart motor controller boards were developed into a robust subsystem that allows for easy reconfiguration of the overall propulsion system with interchangeable components. More then 20 computer boards were produced out-of-house and integrated into the grouper system.

Further, towards the sensing and navigation system, we have performed testing of an RF-modem for underwater communication in the test tank. A highly accurate temperature sensor with a smart interface was developed as part of an undergraduate student project. We have acquired several fiber optic gyros as a heading reference for the individual vehicles. The interface and a data-buffer board were designed and tested and await implementation. We have made significant progress on the development of a vision-based heading module using position sensitive devices (PSDs). Two student projects contributed to this effort. The PSD work is in progress as we aim to use the technology for relative position/heading measurements of neighboring vehicles. Another student project implemented the first stage of the Blob trackers on a mock-up vehicle in stereo mode and performed a system performance study with a pan and tilt system using COTS servos. A global (tank-fixed) vision system with an appropriate frame grabber was installed in the tank allowing for real-time vehicle monitoring and recording as well as providing the framework for future computer vision experiments. The acoustic navigation system has been installed in the tank and we are currently working on the ping

synchronization. An acoustic Doppler velocity meter was installed and tested on a grouper vehicle and is expected to considerably improve the positioning system. A second Doppler was tested and awaits integration in a new grouper vehicle. In an effort to facilitate controller development and implementation we have just concluded the development of a driver for the fiber optic gyros to be utilized on a single board computer (PC104) with Matlab XPC-target. This allows us to design and implement controllers into the vehicle's main computer using standard sensor and, in the near future, actuator blocks without cumbersome coding. This approach benefits heavily from the communication architecture and the smart interfaces of sensors and actuators implemented on the vehicles. For real-time data visualization we designed a virtual environment for the Grouper vehicle that allows the user to replay the collected attitude and position information through a web-based interface.

RESULTS

Early closed-loop control of the grouper prototype showed the feasibility of hardware-in-the-loop development by using standard software tools to design and tune the vehicle controllers on-line. We established that a controller update rate of 10Hz is sufficient for our system. Early progress on sensing and navigation using PSDs shows promise for their use in heading and position measurement both with respect to a fixed reference as well as a moving reference (neighboring vehicle). As expected, the acoustic system's performance is highly dependent on the echo level present in the tank. Sound-absorbent coating of the wall behind a base stations proved to be one key factor towards obtaining accurate measurements. The distributed communication architecture and the smart interfaces of sensors and actuators implemented on the vehicles provide an easily reconfigured and adaptable testbed. The new real-time software tools showed their potential in making the overall control system user friendly. Initial results on the virtual reality data replay functionality are promising and will be pursued for a real-time display using the RF-communications. The overall system showed its potential in educating and inspiring students and researchers in various related science and engineering projects. Multiple independent student project and senior theses were performed in the framework of this development.

IMPACT/APPLICATIONS

The sensing and navigation system will make it possible to create a multiple-AUV testbed in which control strategies for group coordination can be studied in three-dimensional space. Existing testbeds for group coordination are typically confined to two dimensions; for example, robotics researchers use mobile robots on the ground to investigate coordinating controllers. Furthermore, fluid dynamic effects between vehicles can be examined in the multiple-AUV testbed. While coordinating strategies for multiple vehicles should be tested at sea, a laboratory testbed makes it possible to develop and test these strategies beforehand (and afterwards) in a readily accessible environment that can be controlled and manipulated as desired. That is, the multiple-AUV testbed can be used as a proving ground to prepare for the at-sea trials. In our other underwater vehicle research projects, e.g., the underwater gliding project, we have found such laboratory testbeds invaluable both for research and education.

Research in coordination of a fleet of AUVs has the potential for significant impact since it is expected to be useful for effective and efficient adaptive ocean sampling that would not otherwise be possible with individual vehicles.

RELATED PROJECTS

This DURIP project is closely related to my ONR projects on Underwater Glider Dynamics and Control and Underwater Glider Networks for Adaptive Ocean Sampling. The advantages associated with underwater gliders are expected to be greatest when multiple gliders are operated cooperatively in a network. These two ONR projects are part of the Autonomous Ocean Sampling Network (AOSN-II) project and the Monterey Bay Field Experiment 2003. A central part of this project and upcoming experiment is to provide adaptive sampling using a group of underwater gliders for the purpose of ocean prediction. See http://www.princeton.edu/~dcsl/aosn

I participate in an NSF/KDI funded project joint with A.S. Morse (Yale), P. Belhumeur (Yale), R. Brockett (Harvard), D. Grunbaum (U. Washington) and J. Parrish (U. Washington) on coordination of natural and man-made groups. We are studying schooling of fish and "schooling" of autonomous underwater vehicles. Development of the Princeton multi-vehicle testbed was initiated as part of this project.

I also have an AFOSR funded project on Coordinated Control of Groups of Vehicles. This is a joint project with V. Kumar and J. Ostrowski at the University of Pennsylvania. A focus of the project is understanding cooperation in the context of coordinated control of distributed, autonomous agents, and the collection and fusion of the sensor information that they retrieve. The testbed is ideal for testing in this context.

PUBLICATIONS

Bachmayer, R. and N.E. Leonard, "Experimental Test-bed for Multi-Vehicle Control, Navigation and Communication", *Proceedings 12th International Symposium on Unmanned Untethered Submersible Technology*, Durham NH, 2001 [published].

Leonard, N.E. and E. Fiorelli, "Virtual Leaders, Artificial Potentials and Coordinated Control of Groups", *Proceedings of the 40th IEEE Conference on Decision and Control*, 2001, 2968-2973 [published, refereed].

Smith, T.R, H. Hanssmann and N.E. Leonard, "Orientation Control of Multiple Underwater Vehicles with Symmetry-Breaking Potentials," *Proceedings of the 40th IEEE Conference on Decision and Control*, 2001, 4598-4603 [published, refereed].

Bachmayer, R. and N.E. Leonard, "Vehicle Networks for Gradient Descent in a Sampled Environment", *Proceedings of the 41th IEEE Conference on Decision and Control*, 2002 [published, refereed].

Bhatta, P. and N.E. Leonard, "Stabilization and Coordination of Underwater Gliders", *Proceedings of the 41th IEEE Conference on Decision and Control*, 2002 [published, refereed].

Ogren, P., E. Fiorelli and N.E. Leonard, "Formations with a Mission: Stable Coordination of Vehicle Group Maneuvers," *Proceedings. 15th Int. Symposium on Mathematical Theory of Networks and Systems*, 2002 [published].

Moreau, L., R. Bachmayer and N.E. Leonard [2003], Coordinated gradient descent: a case study of Lagrangian dynamics with projected gradient information, *Proc. 2nd IFAC Workshop on Lagrangian and Hamiltonian Methods for Nonlinear Control,* [published, refereed].

Graver, J.G., R. Bachmayer, N.E. Leonard and D. M. Fratantoni [2003], Underwater Glider Model Parameter Identification, *Proc.13th Int. Symp. Unmanned Untethered Submersible Tech.*, [published].

Fiorelli,E., P. Bhatta, N.E. Leonard and I. Shulman [2003], Adaptive Sampling Using Feedback Control of an Autonomous Underwater Glider Fleet, *Proc.13th Int. Symp. Unmanned Untethered Submersible Tech.,,* [published].

Ogren, P., E. Fiorelli and N. E. Leonard [2003], Cooperative Control of Mobile Sensor Networks: Adaptive Gradient Climbing in a Distributed Environment, *IEEE Transactions on Automatic Control.*

Nair, S., N.E. Leonard and L. Moreau [2003], Coordinated Control of Networked Mechanical Systems with Unstable Dynamics, *Proc. 42nd IEEE Conference on Decision and Control,* [in press, refereed].

Sepulchre, R, D. Paley and N.E. Leonard [2003], "Collective motion and oscillator synchronization," in *Proceedings Volume from the Workshop on Cooperative Control,* Springer-Verlag, [in press].

Ogren, P. and Naomi Ehrich Leonard [2003], Obstacle Avoidance in Formation, *Proc. IEEE International Conference on Robotics and Automation*, [published, refereed].

Ogren, P. and Naomi Ehrich Leonard [2003], A Convergent Dynamic Window Approach to Obstacle Avoidance, *IEEE Transactions on Robotics and Automation*.

HONORS/AWARDS/PRIZES

N.E. Leonard, Princeton University, Plenary lecture at the Society of Industrial and Applied Mathematics (SIAM)'s Conference on Applications of Dynamical Systems, May 2003.